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INVESTIGATION OF IMPACT FLASH [redacted]

AT LOW AMBIENT PRESSURES

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ABSTRACT

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The luminosity produced by aluminum projectiles impacting aluminum targets at a velocity of 2.5 kilometers per second has been measured in a small test chamber at ambient air pressures from 4×10^{-4} to 2×10^{-1} millimeters of mercury. The luminosity after impact is found to vary directly with pressure to a power less than 1. Spectral lines characteristic of the target and projectile material have been identified in impacts of aluminum projectiles into the following targets: (a) aluminum, (b) aluminum coated with sodium silicate, and (c) solid rock.

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INTRODUCTION

This investigation of impact flash was begun to determine the feasibility of a proposal by Dr. John O'Keefe of the National Aeronautics and Space Administration's Goddard Space Flight Center. O'Keefe proposes to drop a mass on the dark side of the moon, observe the spectrum of the flash produced on impact, and so determine the chemical constitution of the lunar surface. The success of the proposal depends upon the production of sufficient radiation containing spectral line and band structure, as opposed to grey-body continua, to permit qualitative analysis of the materials present in the absence of an atmosphere. The atmospheric pressure at the surface of the moon is thought to be less than 10^{-12} earth atmospheres (ref. 1).

Early work in this field has been conducted at the University of Utah by Clark, Kadisch, and Grow (ref. 2). They found that atomic copper lines are the predominant feature of the flash obtained from impacting copper spheres into copper targets at a velocity of 2.2 km/sec in an atmosphere of argon at a pressure of 60 torr, or 60 mm of Hg. In an atmosphere of hydrogen at a pressure of 635 torr, however, the line structure is not detectable, and the flash is dimmer by at least two orders of magnitude. They concluded that impact flash results primarily from the collisions between spray particles ejected from the crater and the surrounding atmosphere, and thus presented a qualitative theoretical explanation for this difference (see Theoretical Considerations). On the other hand, Gehring and Sieck (ref. 3) studied the flash from the impact of nylon spheres with sand targets at velocities of 2.1, 2.6, and 3.1 km/sec, and found, in tests with air at pressures from 4×10^{-2} to 80 torr and with helium at pressures of 4 and 76 torr, no apparent significant effect of the composition or the pressure of the gas surrounding the area of impact on the magnitude of the impact flash.

The present paper deals with the onset and spectrum of radiation due to impact of aluminum projectiles into aluminum and basalt rock targets. The onset of radiation has been reported here because the effects of confining the test in a small volume may change the peak intensity and total radiated energy. The onset, on the other hand, should not be affected because the volume from which the radiation emanates lies well short of the walls.

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THEORETICAL CONSIDERATIONS

The spectrum of a self-luminous event is expected to consist of line emission by atoms, band emission by molecules, and a continuum by the hot surfaces of solids and liquids. In an impact event, all three are expected to be present. Because grey-body radiation carries little information about the chemical constitution of the emitter, the present analysis is restricted to line and band spectra only.

If, during cratering, there is a mechanism by which the atoms and molecules of the target and projectile material can be vaporized and excited, the radiation so produced would be independent of the atmosphere surrounding the target. Radiation produced from the interaction of ejecta and atmospheric particles would be, however, dependent upon the atmosphere. Ejecta traveling at velocities as much as triple the impact speed have been observed; this high-speed matter may be expected to radiate in the same manner as meteors if a gas is present.

Atoms and molecules can be excited by absorbing incident radiation or by a transfer of kinetic energy from other atoms or molecules. Energy producing excited electronic states can be accepted by the atom or molecule only in discrete quantities or quanta. The excited atom or molecule can then decay to a lower state by the emission of a photon. The primary process of excitation of atoms and molecules is by collision with other particles. Let us consider an interaction, scattering, between two particles of mass m_1 and m_2, from which a photon, of energy $h\nu$, may be emitted. Let particle 2 be initially at rest and particle 1 have the velocity V. The equations for the conservation of energy and momentum are

$$1/2 m_1 V^2 = 1/2 m_1 v_1{}^2 + 1/2 m_2 v_2{}^2 + h\nu$$

$$m_1 \bar{V} = m_1 \bar{v}_1 + m_2 \bar{v}_2 + (h\nu/c)\bar{k}$$

where v_1 and v_2 are the respective particle velocities after scattering, h is Planck's constant, ν the frequency of the emitted radiation, and c the velocity of light. The bars in the momentum equation indicate vectors and $\bar{k}$ is a unit vector in the direction of propagation of the photon. Solving these for a minimum V, for a photon of frequency ν to be emitted, we arrive at a threshold equation for the relative velocity between the two particles.

$$V_{min} = \sqrt{\frac{2(m_1 + m_2)h\nu + (h\nu/c)^2}{m_1 m_2}}$$

Table I contains values of V_{min} computed from this equation. For each value, particle 1 is an aluminum atom and ν is the frequency of radiation emitted by an aluminum atom when an electron jumps from its first excited state to the ground state.

TABLE I

$\nu = 7.57 \times 10^{14} sec^{-1}$ (3962 A.U.)
Particle 1: aluminum atom

Particle 2	V_{min}, km/sec
Lead atom	5.0
Aluminum atom	6.7
Nitrogen molecule	6.6
Argon atom	6.1
Helium atom	13.2
Hydrogen molecule	17.9

Radiation produced solely by interaction of projectile and target is expected to depend upon the projectile mass, shape, and velocity and the materials involved. All other factors remaining equal, table I shows that higher atomic or molecular weights of the target material lead to lower threshold velocities, and therefore to an increased probability of satisfying the threshold condition for excited states. Also the specific energy in the impact zone, temperature and pressure, is generally greater for higher target atomic or molecular weights. This effect should also increase the amount of radiation for targets of high atomic or molecular weights.

The same considerations show that radiation produced by ejecta interacting with the atmosphere should depend on atmospheric composition. If all variables except ambient pressure are held constant, higher pressure and therefore higher atmospheric density should result in a compressed time scale and hence a higher rate of increase of luminosity.

DESCRIPTION OF APPARATUS

The apparatus (fig. 1) consisted of the gun, the range, and the instrumentation. A commercial 220 Swift sporting rifle was used to fire sabot-mounted, 1/8-inch-diameter aluminum spheres at a velocity of 2.5 km/sec. This velocity is approximately equal to lunar escape velocity, the proposed impact velocity of the Ranger rocket on the moon. The sabot-mounted model was fired into a blast tank containing gas at pressures of about 400 torr, where the sabot and powder gases were stopped. The range consisted of an impact chamber, 11×11 cm in cross section, and a 10-foot length of stainless steel pipe connecting the chamber to the blast tank.

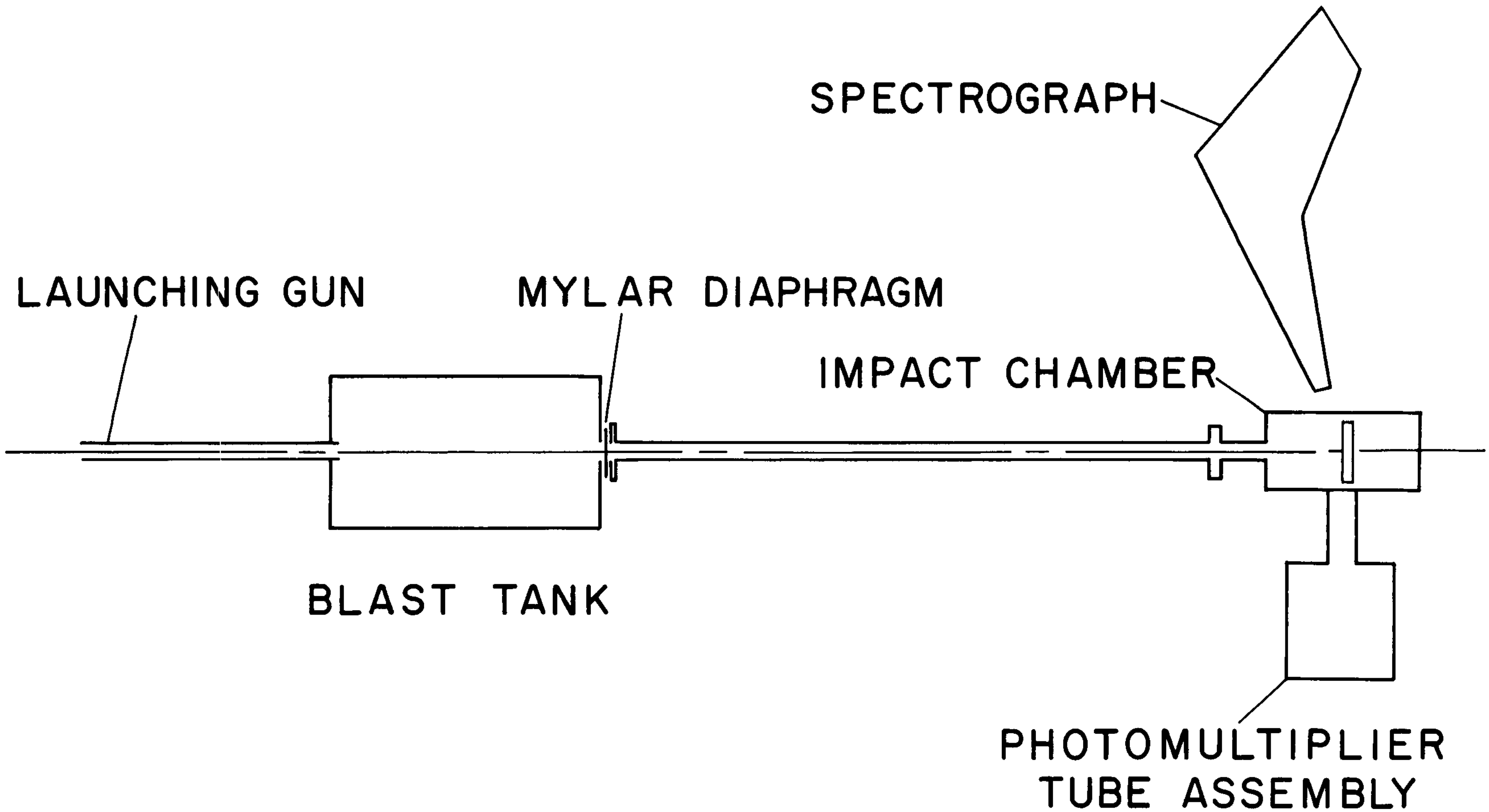

Figure 1.- Gun, range, and instrumentation.

A 1/2-mil mylar diaphragm between the blast tank and steel pipe separated the range from the blast tank. The diaphragm was sufficient to maintain the pressure difference of 400 torr and yet not fracture the penetrating model. The 10-foot length of pipe prevented the blast-tank gases from reaching the test chamber until after the luminosity measurements had been made. The range could be evacuated to 10^{-4} torr with a 4-inch oil diffusion pump. Range pressure was measured with a McLeod type gage. The inside of the impact chamber was blackened to reduce reflected light. The time variation of luminous intensity of the flash was measured with a DuMont 6292 photomultiplier tube. This tube is sensitive to radiation between the wavelengths 3500 and 5500 A.U., or approximately half the visible spectrum. The absolute spectral response of the entire optical train was measured using a ribbon filament lamp, calibrated by the National Bureau of Standards, and a grating monochrometer. The photomultiplier tube, together with a calibrated neutral density filter, was arranged as a "pinhole camera" (fig. 2) with the optical axis in the plane of the target surface. The volume in the test chamber viewed by the system contained all points within approximately 4 centimeters of, and uprange of, the optical axis. The phototube output was recorded on two oscilloscopes which provided time axes. One oscilloscope was triggered by breaking a thread of silver painted on the mylar diaphragm. This oscilloscope recorded peak luminosity and an accurate measurement of the time between rupture of the diaphragm and impact, from which projectile velocity was calculated. The second oscilloscope, triggered internally by the flash and sweeping at a much faster rate, measured the variation of luminosity with time. On several rounds a Huet CI spectrograph, with a camera lens aperture of f/0.7 and a dispersion of 150 A.U. per mm at 4350 A.U. and 500 A.U. per mm at 5500 A.U., was used to record spectra.

RESULTS AND DISCUSSION

Luminosity Studies

Figure 3 shows two oscilloscope traces of luminosity produced by 1/8-inch aluminum spheres impacting aluminum targets in air at ambient pressures of 1.6×10^{-3} torr, and 8×10^{-2} torr. The impact flash at 1.6×10^{-3} torr is double peaked. The second peak occurs shortly after the fastest particles of ejecta strike the impact chamber walls. At 8×10^{-2} torr the luminosity from secondary impacts is nearly masked by the primary impact flash. At the highest test pressure the secondary impact radiation appears to be suppressed. It should be stated again that the luminosity measurements refer to radiation between the wavelengths 3500 and 5500 A.U. from a small volume about the impact point. Figure 4 is a log-log plot of the initial rate of increase of luminosity in watts per 4π steradians per microsecond versus ambient pressure. The reason for selection of this parameter is discussed in the Introduction. This plot, which covers a range of pressures from 4×10^{-4} to 2×10^{-1} torr, shows

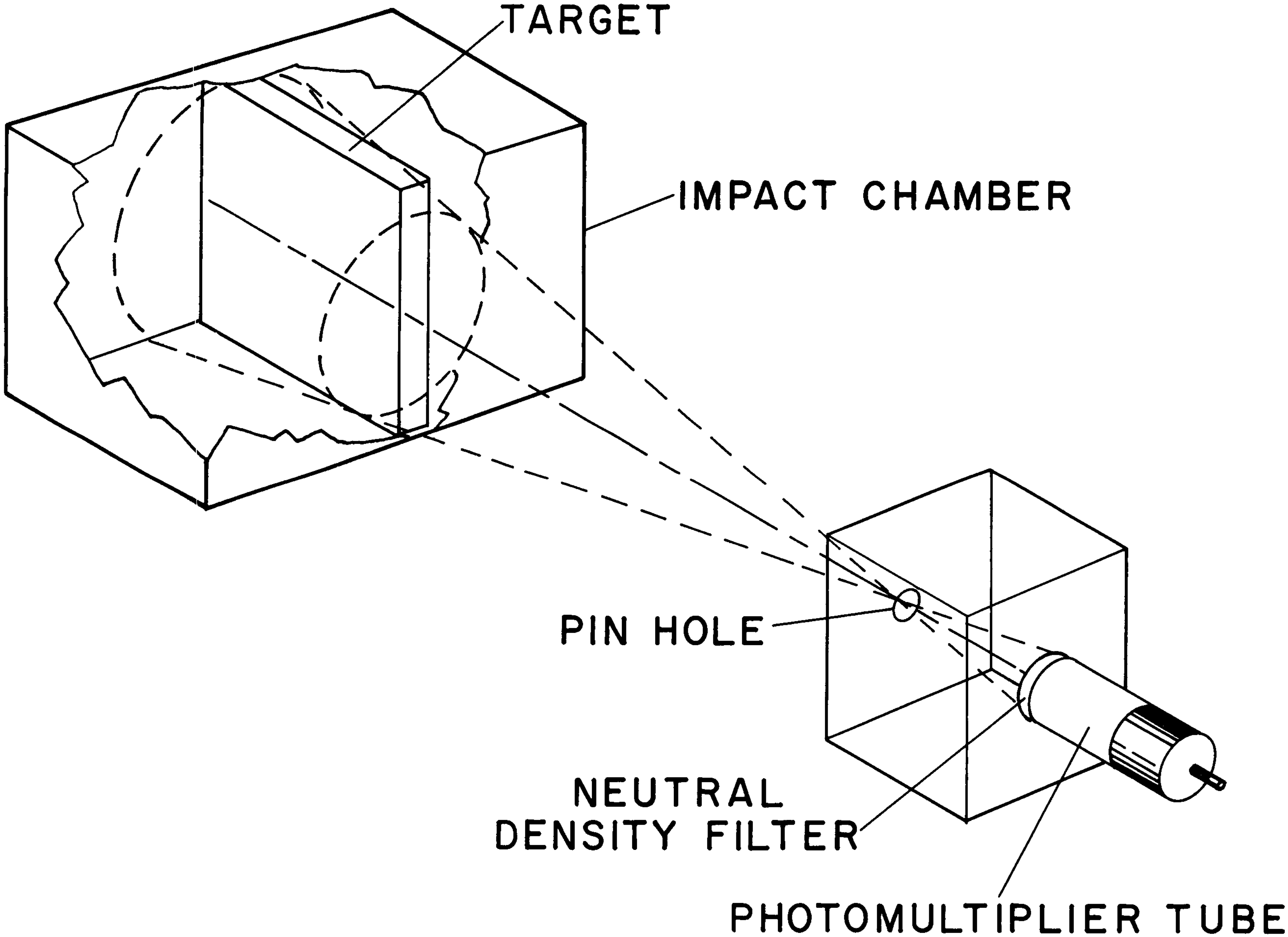

Figure 2.- Photomultiplier-tube assembly.

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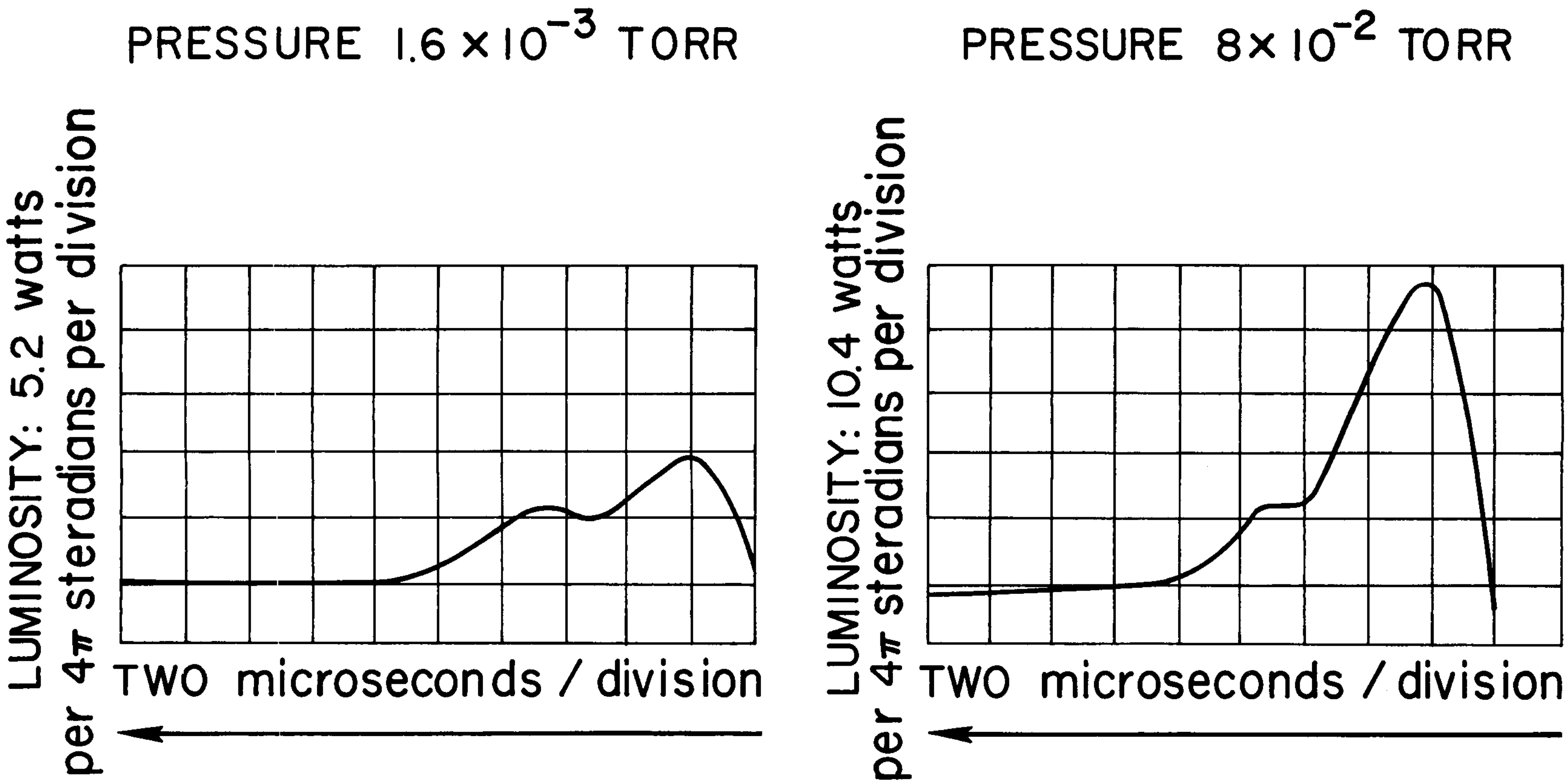

Figure 3.- Photomultiplier-tube-oscilloscope traces.

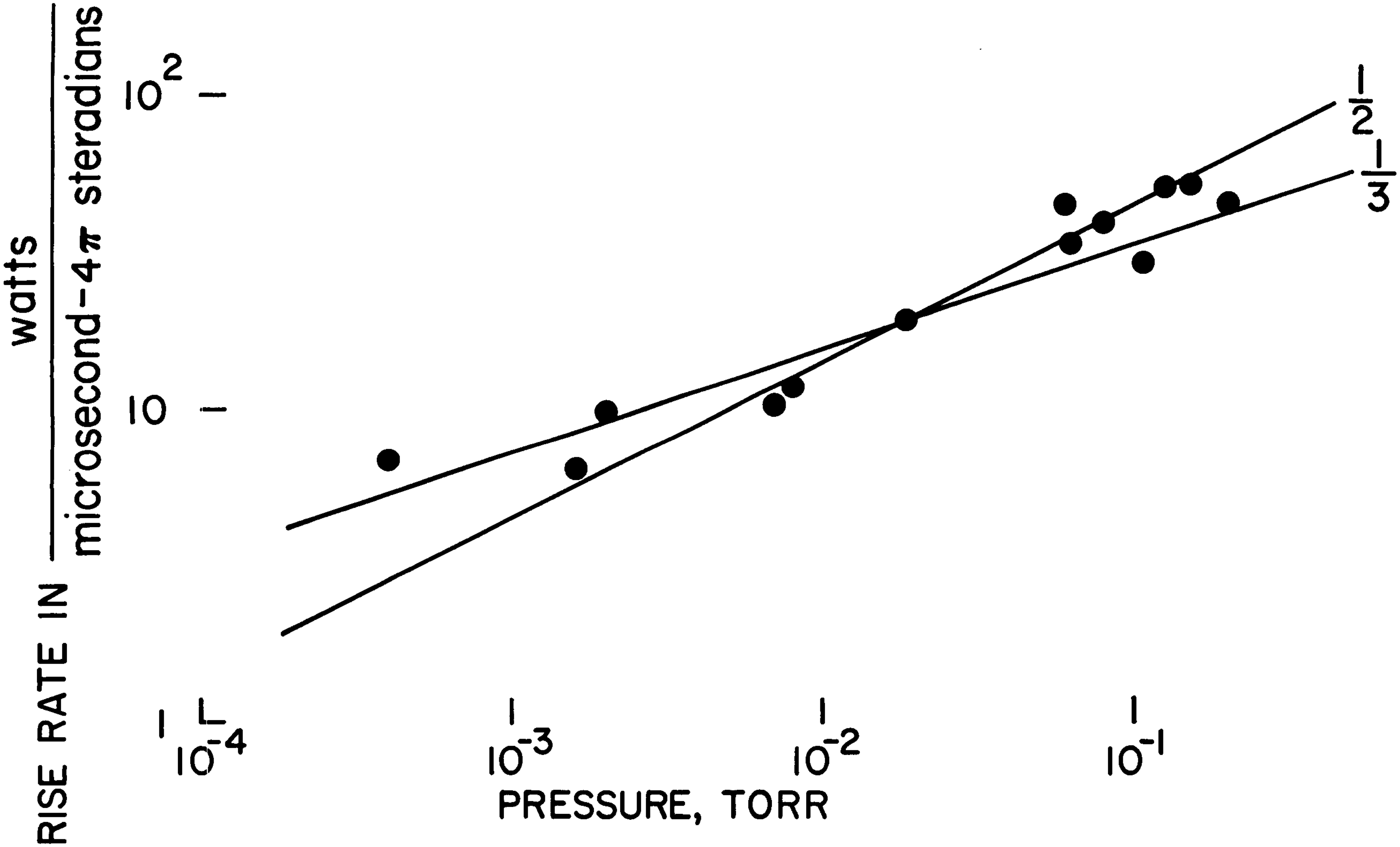

Figure 4.- Rise rate of luminosity versus pressure.

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that the onset rate of luminosity varies approximately as the cube root of the ambient pressure, which is qualitatively consistent with Clark, et al. The duration of flash, the time from initiation to the decay to one-half peak value, is approximately 4 to 5 microseconds for pressures below 10^{-1} torr, but this may be influenced by the test-chamber size. The energy of radiation calculated from the area beneath the luminosity-time curve on the oscilloscope traces is of the order of 10^{3} ergs at 10^{-2} torr, or about 10^{-4} percent of the projectile kinetic energy.

Spectrographic Studies

Since the ultimate application of the present test results rests on analysis of spectra, several tests were recorded with a conventional visible-light spectrograph.

Figure 5 shows three densitometer traces of spectra obtained from impact flash. The top trace is for an aluminum target coated with sodium silicate and an ambient air pressure of 8×10^{-4} torr. The predominant feature is the atomic sodium D doublet at about 5890 A.U. Two lines are also detectable at about 3950 A.U., the approximate wavelength for radiation from excited aluminum atoms. The presence of these latter lines indicates a fairly large number of collisions at velocities greater than the threshold of 6.6 km/sec (roughly 2.6 times the impact velocity). For the middle trace the target was aluminum without sodium silicate and the ambient pressure was 1.2×10^{-3} torr. The predominant features are the same two lines of aluminum at 3944 and 3962 A.U. Manganese line structure is seen at 4034 A.U. along with the unavoidable sodium. Bands consistent with those expected for AlO are also present. Manganese is found by chemical analysis to be present in the aluminum alloys of both the target and projectile and also, it should be added, in the steel of the impact chamber; sodium is found on everything. Sodium D line radiation was found on all spectra. Basalt rock was the target for the bottom trace and the ambient pressure was 2×10^{-1} torr. The lines of sodium, calcium at 4227 A.U., and aluminum and the bands of aluminum oxide are detectable. Sodium, aluminum, and calcium, also an exceptional radiator, are found in basalt as oxides. Aluminum in the projectile may mask the effect of aluminum in the rock.

CONCLUDING REMARKS

The rate of onset of luminosity from high-speed impact depends upon the atmosphere surrounding the target. This result is consistent with those of Clark and appears to disagree with those reported by Gehring 10

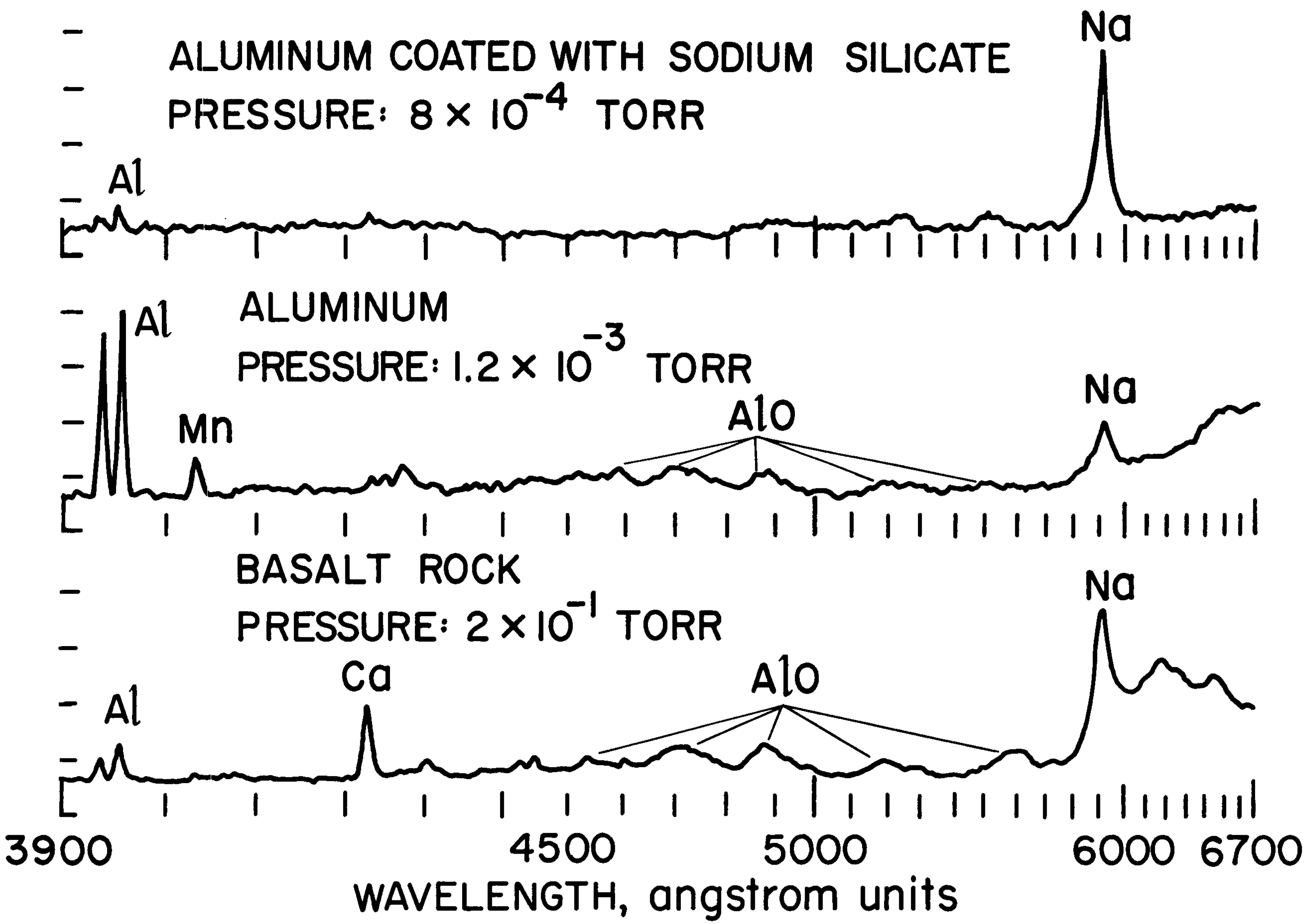

Figure 5.- Densitometer traces.

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and Sieck. A possible explanation for this disagreement centers on the fact that the luminosity measurements of Clark, as well as those of this paper, were made of a metal impacting a solid and Gehring and Sieck's were made on a plastic impacting a granular material. In the shocked impact region, the pressure, which is responsible for the acceleration of ejecta, is expected to be greater for a metal impacting a solid than for a plastic impacting a granular target. The luminosity, produced by ejecta interacting with the atmosphere, may not constitute a significant quantity of radiation in Gehring and Sieck's tests. The principal part of their luminosity measurements may be radiation produced entirely by the mechanics of cratering.

At the low ambient pressures of the present tests the observed spectra contain line and band features consistent with the elements known to be present.

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